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REPEATABILITY, ACCURACY, PORTABILITY, AND ERRORS OF THE PORTABLE ALIGNMENT GYROCOMPASS SYSTEM

by John J. Mihm and Richard A. Murphy

Electronics Research Center

Cambridge, Mass. 02139

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16. Abstract The precision alignment gyrocompass (PAG) system, a prototype system, was thoroughly evaluated at one laboratory and used at a second laboratory.

A wealth of information describing potential error sources such as draft sensitivity, warm-up time, creep, seismic disturbances, and their circumvention was generated. System repeatability is discussed as it affects operating procedures.

Two-position, four-position, and H-modulation gyrocompass techniques were studied, tested, and evaluated.

At one location, the PAG absolute system accuracy was checked against a precision astronomically referenced azimuth in a very quiet and stable suburban environment. At the second location, in a noisy urban area, an optical azimuth reference was established using the PAG.

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SUMMARY

Evaluation testing of the portable alignment gyrocompass (PAG) system was conducted at NASA/ERC, Cambridge, Mass., and the Precision Products Department of Northrop Nortronics in Norwood, Mass., during the period of April 1968 to June 1969. The PAG system, used as a four-position gyrocompass, demonstrated a long-term azimuth capability of ±8.5 arc seconds absolute accuracy, exhibited short-term shifts of up to 5 arc seconds, and provided data to prove that proper operating technique is essential. As a two-position gyrocompass, the PAG system demonstrated a 25 arc-second data spread. The wheel-speed modulation testing was inconclusive.

INTRODUCTION

The NASA/ERC gyrocompass, as manufactured by TRW, incorporates seven different modes of operation, thus providing a flexible, highly accurate tool which permits an evaluation of various modes of gyrocompassing.

This system utilizes a precision rate integrating gyro for accurately determining the Earth's rotation axis. This axis was compared with an astronomically determined North. This gyrocompass has been demonstrated to be very accurate in a laboratory environment. The design objective was a portable gyrocompass for precision determination of a first-order azimuth (1-second accuracy). The system was accepted to a 5-arc-second standard deviation accuracy specification. Four position (gyrocompassing), as recommended by TRW, was the prime technique utilized.

INSTRUMENT DESCRIPTION

The precision alignment gyrocompass (PAG) system consists of a programmable platform sensor package (PSP), electronics control assembly (ECA) with cable, and a standard Beckman Model 1453 printer. See Figure 1 for a typical block diagram.

The PSP houses a precision gas bearing Nortronics GI-T1-T gyro mounted in the center of a set of gimbals (Figure 2). The gimbals and gyro are mounted inside a magnetic and draft shield. The gyro is thermally controlled from the ECA. The ECA contains all power and torque to balance servo loop closure circuitry for the gyro, position servos for gimbals, programming logic, counting circuits for torque rebalance current integration, and spin axis angular displacement readout. The printer records the ECA outputs.

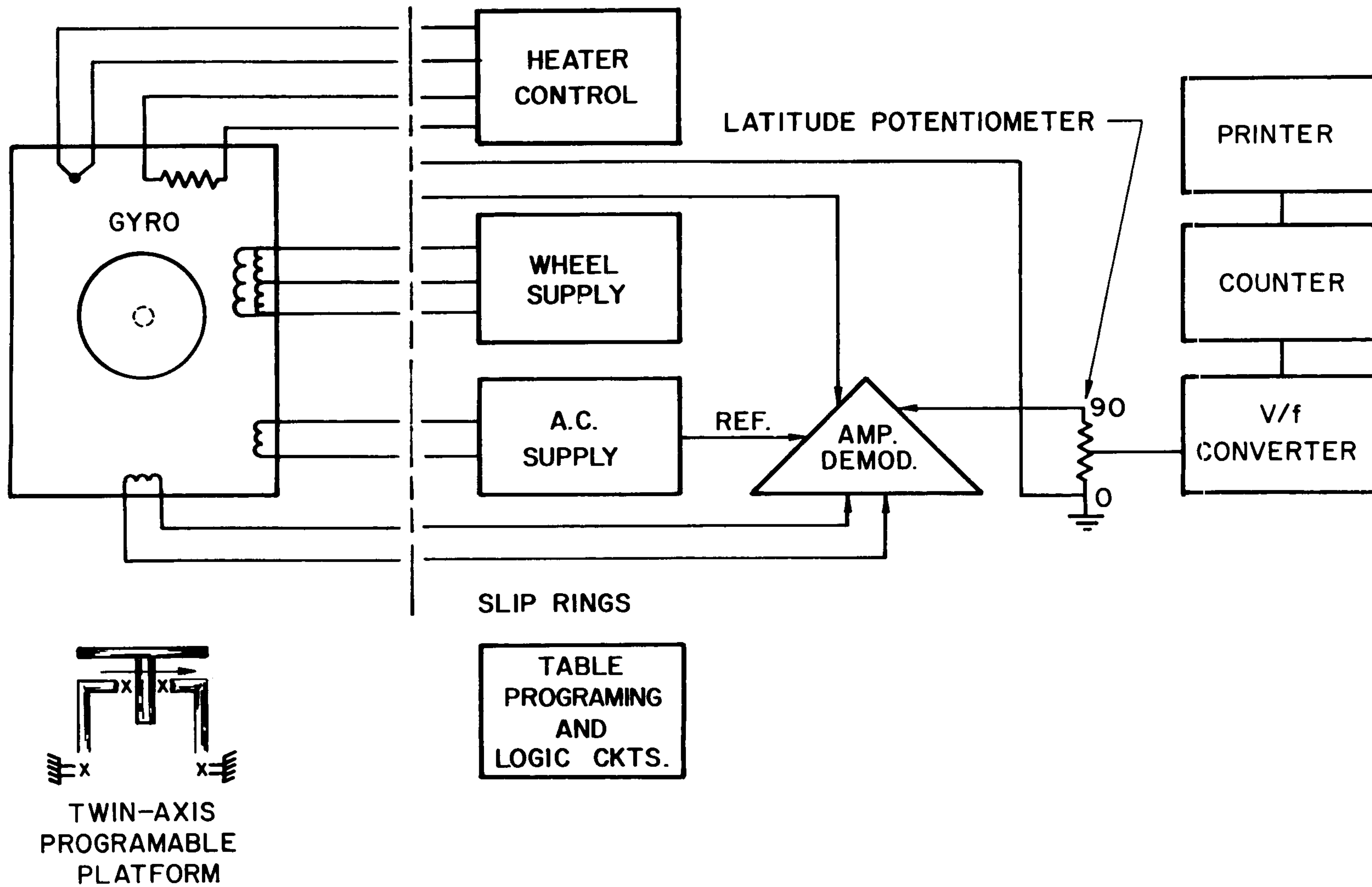


Figure 1.- Typical PAG-type implementation

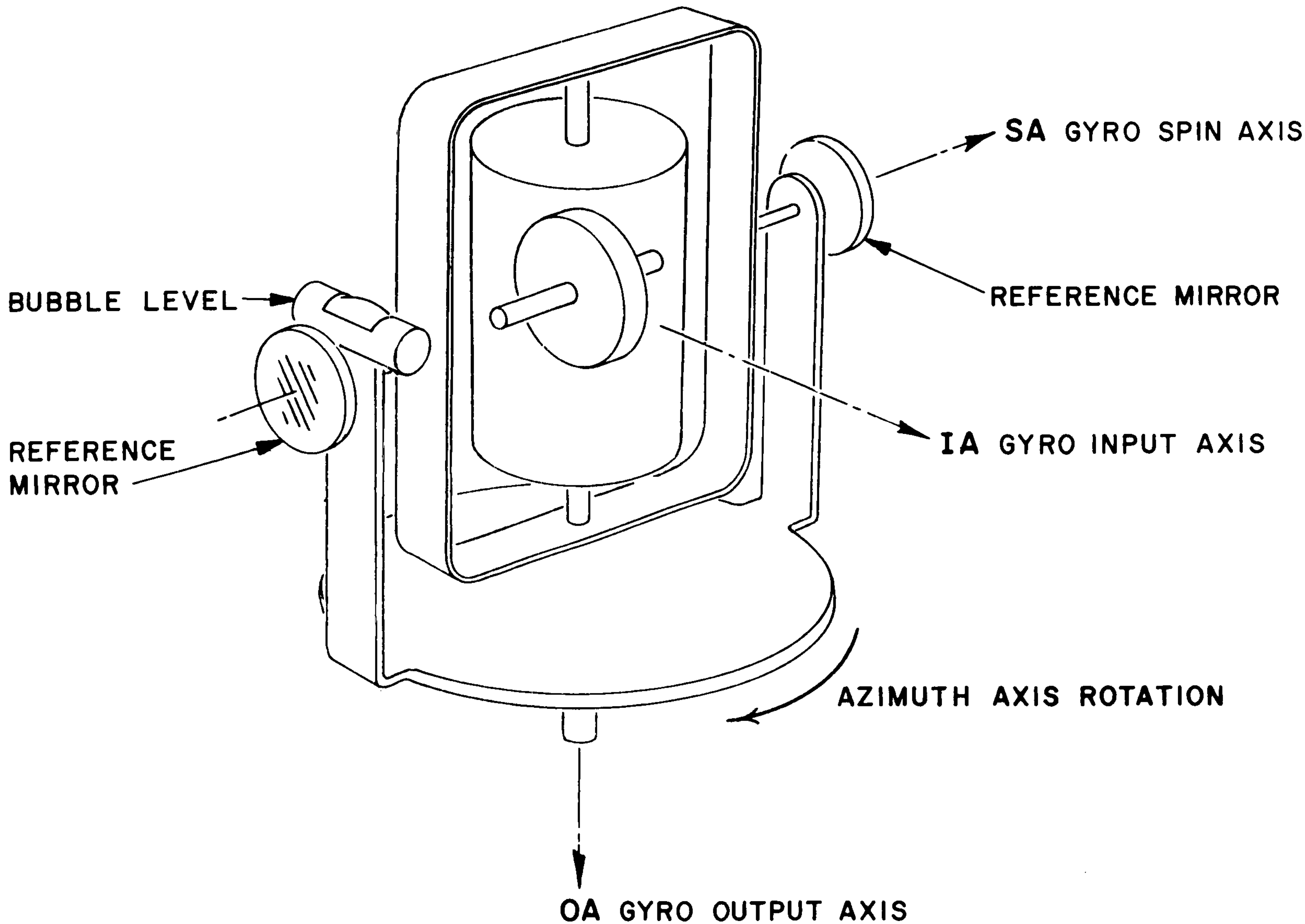


Figure 2. - PAG system axis identification to reference minor

The angular displacement is displayed in arc seconds, which is the relative misalignment of the gyro spin axis from the Earth's spin vector. The latitude potentiometer is used to correct for the cos β decrease in the peak torque seen on the gyro as it is moved North or South in latitude from the equator in an OA vertical orientation.

OPERATING MODES

The two principal modes of operation used were the two- and four-position modes. See Figure 2 for axis definition.

The two-position mode (Mode III): In this mode the output axis remains down and the spin axis is sequenced North and South without case reversal.

The four-position mode (Mode I): This mode starts with the gyro spin axis North and the output axis is down; the gyro is then sequenced in the following order: spin axis North – output axis up, spin axis South – output axis down, and completing the sequence with, spin axis South – output axis up.

PURPOSE

The primary purpose of this study is the absolute accuracy and long-term stability of PAG determinations.

Stability at ERC Azimuth Reference

Since the delivery of the PAG to NASA, it has been used primarily for the calibration of the laboratory optical azimuth references. The azimuth porro prisms are mounted on building columns within the laboratories. NASA/ERC does not have a precise Earth-reference azimuth line and the basic stability of the porro prism shifted on a random basis from a few arc seconds to 5 arc minutes. This raised the question of which system was the major contributor to the error, the PAG system or the laboratory reference.

Gyrocompass Mode Evaluation

In addition, since this system was an advanced prototype of four-position gyrocompassing, it was of interest that follow-on work should be performed to evaluate the two-position vs four-position gyrocompass techniques. As this system will operate in either two- or four-position modes, it provides an excellent tool for a true comparison of the two relative modes using the same gyro and support electronics. It must be understood that four-position gyrocompassing compensates run-to-run (not within a run) errors and also overcomes shifts in the gyro's spin axis. In the two-position mode, any axis misalignment error of the gyro will give a resultant uncertainty. It should be understood that the relative merit of the comparison of two-position vs four-position gyrocompassing techniques will be determined to a large extent by the stability of the gyro used.

Modulation Investigation

Another avenue of investigation was the use of this system for wheel-speed modulation gyrocompassing and/or dead reckoning gyrocompassing for support of strapdown system alignment. NASA/ERC has a prime interest in strapdown systems. Since system alignment of a strapdown system is a problem and gyrocompass systems with rotating axes by definition of strapdown do not strapdown, ERC has an interest in utilizing other gyroscopic principles for Earth's spin axis vector determination. If the same system used for the standard two- or four-position gyrocompass could be utilized, no better comparative evaluation could be attained. The most common non-rotating gyrocompass technique used is called dead-reckoning. In this technique the gyro is positioned spin axis North and both the bias trim and readout mirror are adjusted. From this point, the gyro bias and spin axis vectors are assumed constant (dead-reckoning). A second not so common technique is called wheel-speed modulation or simply modulation gyrocompassing. This technique assumes the gyro spin axis vector to be constant but does not rely on the bias remaining constant. It does, however, assume the full- to half-speed change in bias to be constant.

Error Source Determination

While performing some of the gyrocompassing tests, associated measurements to determine the effects of ambient temperature variations, drafts, vibrations, and noise were investigated.

APPROACH

The basic philosophy used in performing the tests was to provide a test environment as benign as possible in all aspects; then through controlled inputs determine the various parameter sensitivities. The requirements of such a benign facility were:

(1) A well-established azimuth reference system with sufficient data to know all its characteristics. (This is important in establishing the capability to optically use the PAG system output.)

(2) A seismic block or other test bed which would provide a high degree of isolation from cultural noise and high angular stability to reduce tilt inputs.

(3) Twenty-four hour operational capability to ascertain any daily cyclic effects.

(4) All standard test laboratory conditions such as regulated lines, ambient temperature controls,

humidity controls, and standard lab-type monitoring equipment.

(5) Personnel experienced in testing inertial grade gyroscopes, familiar with their care and handling.

PPD Nortronics in Norwood, Mass., fulfilled the requirements and, in addition, was the manufacturer of the gyroscope used in the PAG system. The data obtained in this testing were subjected to statistical analysis techniques. It was also decided that seismic measurements would be made at the PPD facility and NASA/ERC laboratories. A sample of the data obtained from this testing and data showing the predictability of gyro output content vs the square of seismic input are included later in the report.*

RESULTS

The first four-position tests were held to (1) determine basic relationships such as standard deviation vs settling time, and (2) calibrate the scale factor vs latitude potentiometer setting. The data in Table I were obtained for settling times vs standard deviation.

Table I

SETTLING TIME vs STANDARD DEVIATION

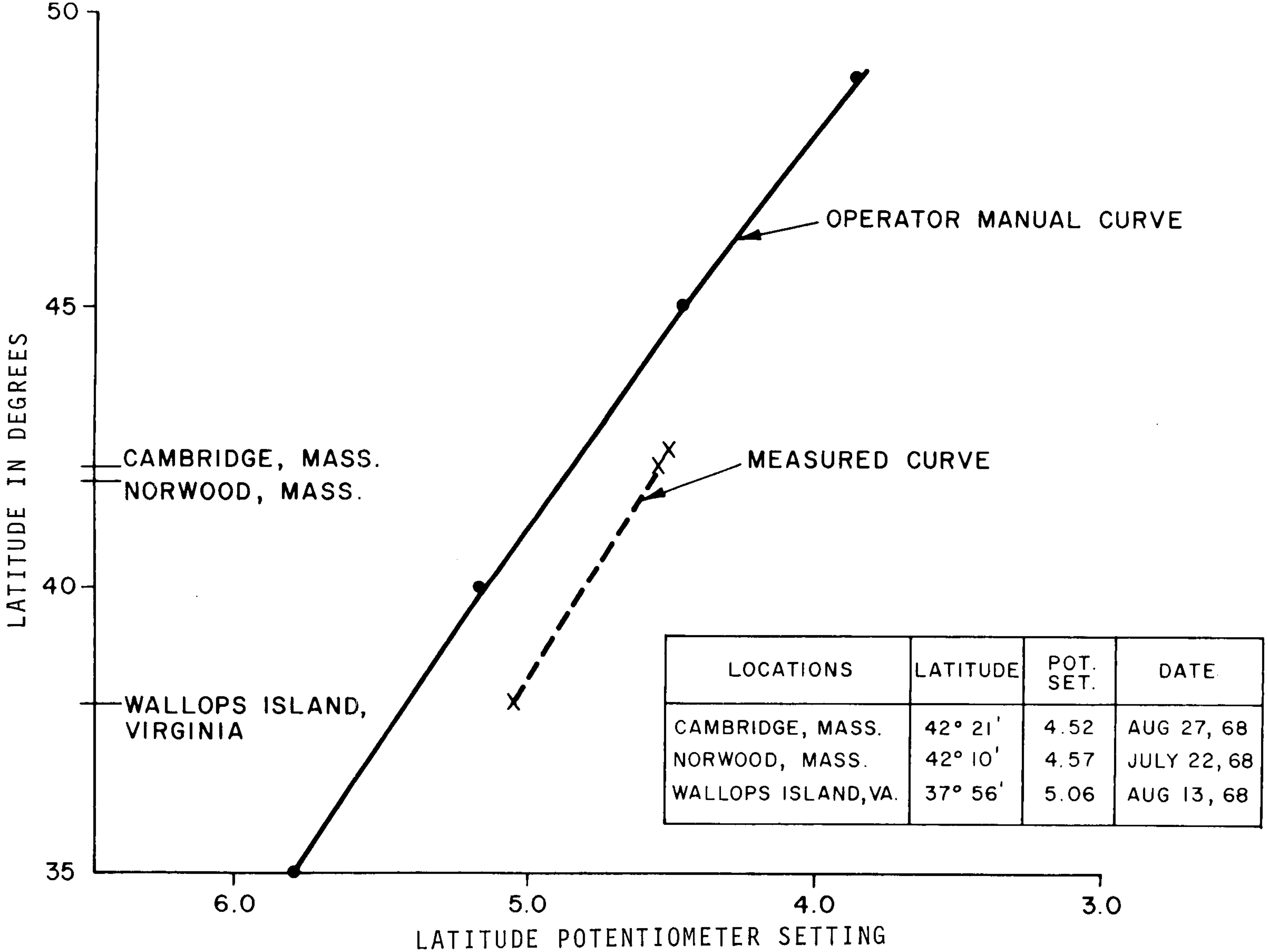
Rest Time*		*Rest time is time (sec) allowed for inertial sensor to restabilize after being disturbed.		
Azimuth (sec)	Rotation (sec)	Sample Period (sec)	No. of Observations	Std. Dev. (arc-sec)
30	10	100	24	2.76
10	30	100	21	2.04
180	180	100	33	1.35

It was decided, based on anticipated performance and in order to reduce test time, to use the 10-second azimuth and 30-second rotation axis rest times.

The calibration of the latitude potentiometer was determined at ERC, Cambridge, Mass., Wallops Island Station, Wallops Island, Va., and PPD Nortronics, Norwood, Mass. This showed a deviation when compared to the table presented in the TRW operator's manual. The results are more clearly seen plotted and tabulated on Figure 3.

A test of absolute azimuth error vs latitude pot setting was taken during June, August, and December. For a summary of the

*See Figures 11-13.



LOCATIONS	LATITUDE	POT. SET.	DATE
CAMBRIDGE, MASS.	42° 21'	4.52	AUG 27, 68
NORWOOD, MASS.	42° 10'	4.57	JULY 22, 68
WALLOPS ISLAND, VA.	37° 56'	5.06	AUG 13, 68

Figure 3.- Calibration of latitude potentiometer

data, refer to Figure 4. The maximum slope shown in Figure 4 was 0.031-arc-second azimuth error per second of PAG azimuth rotation axis off true North. This meant that an error in pot setting observed on 4 June of 4.35 instead of 4.57 could account for a maximum of 0.62-arc-second azimuth error in any previous data gathered, as the PAG was kept within a 20-arc-second maximum error from true North.

A series of determinations of the PAG system scale factor on an Ultradex Dividing Head (1° increments to ±0.25-arc-second accuracy) was performed at two pot settings. It is interesting to note the linearity of these data shown in Figure 5. It is also of interest that the PAG system is designed to read out on the basis that the sine of the angle and the angle in radians are the same. This is not a correct assumption for large angles when looking for arc-second accuracy. If corrections are made for large angle, the PAG system may be used accurately for $\pm 5^\circ$ angles off true North. Figure 6 shows an example of this error and the resultant curve after correction.

Figure 7 shows the positioning accuracy and repeatability of the gimbal during the four-position and two-position test runs during a 10-day calibration in July and August. The system was operated in Mode I and Mode III. An autocollimator was positioned in front of the system to monitor indexing repeatability of the system. (Refer to Figure 8.) Figure 9 shows a view of the physical hardware.

It can clearly be seen from the data in Figure 7 that for the period 31 July through 6 August that the data showed a repeatability of the spin axis position of less than 1 arc-second. Note that the system was shut down between each successive test. The apparent wandering of the axis shown on the first few data points of 6 and 7 August was averaged out in the final resultant calculation of the spin axis position (non 180° Rot. Pt.). A review of the corresponding azimuth heading data, Figure 10, for this same period of data accumulation (6-7 Aug.) showed no observable spikes or shifts in Mode I which could be attributed to this rotational position shift. Therefore, it is fair to assume that the four-position technique of data acquisition is very forgiving of mechanization problems. This is further highlighted by the shift shown on 7 August for two-position indexing and the corresponding spike on the azimuth heading data. In the two-position Mode III data, the shift in the azimuth heading returned despite the permanency of the positional shift. It should be stressed that the optical shifts of Figure 7 are compensated for in the data plotted in Figure 10. Proper monitoring of the PAG mirrors should be maintained at all times as instrument shifts are possible.

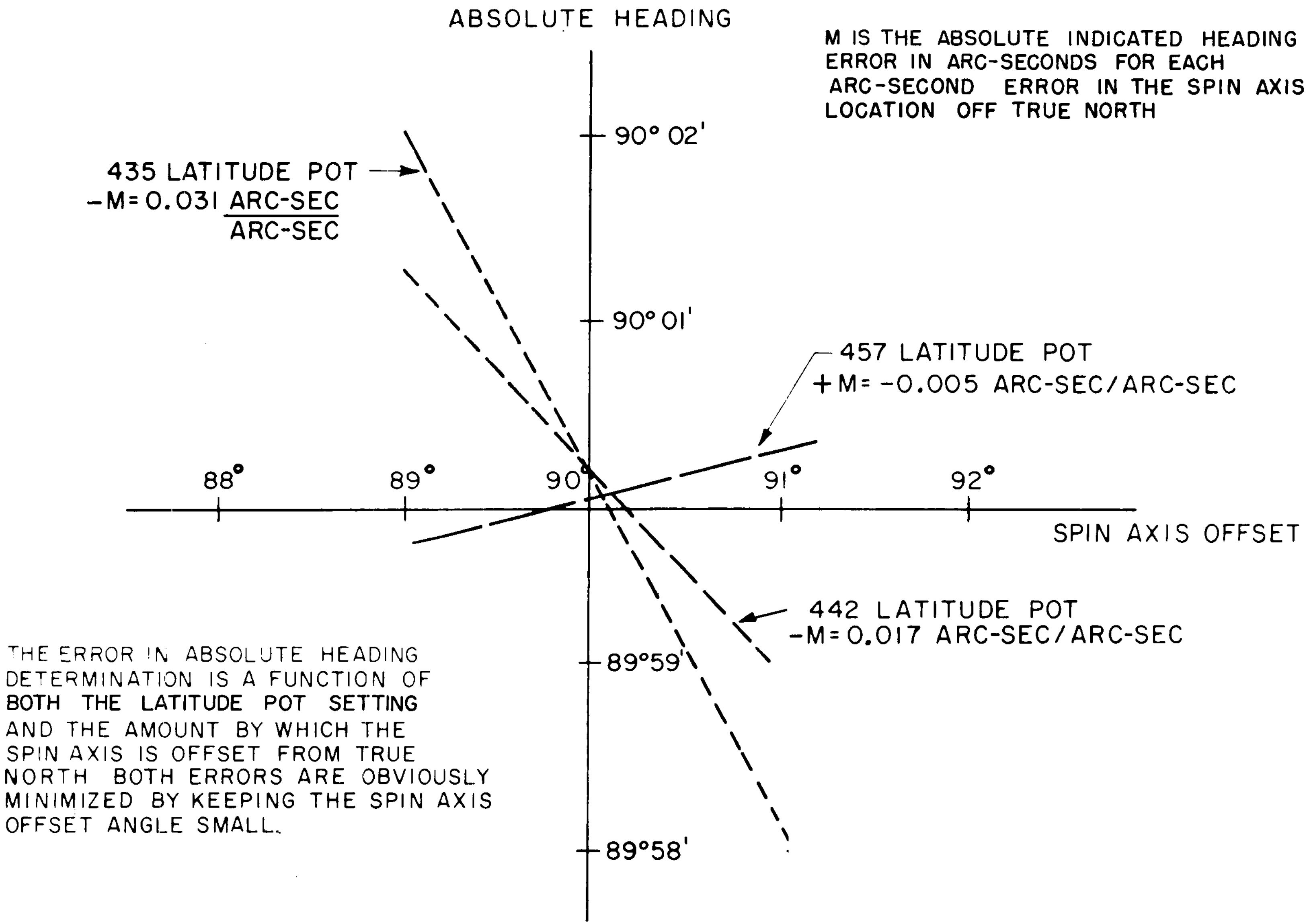


Figure 4.- Absolute heading error vs gyro spin axis offset

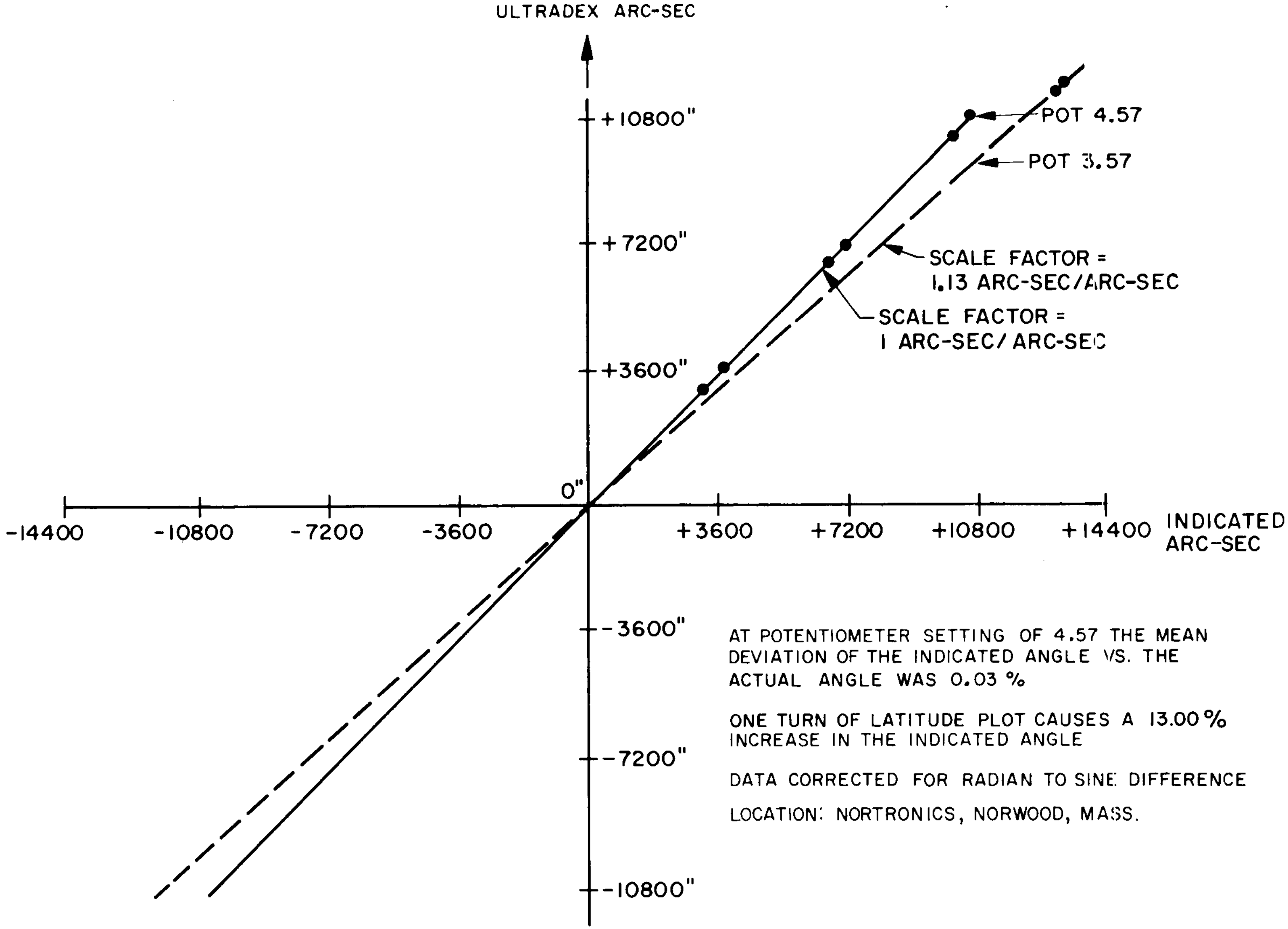


Figure 5.- Scale factor and linearity

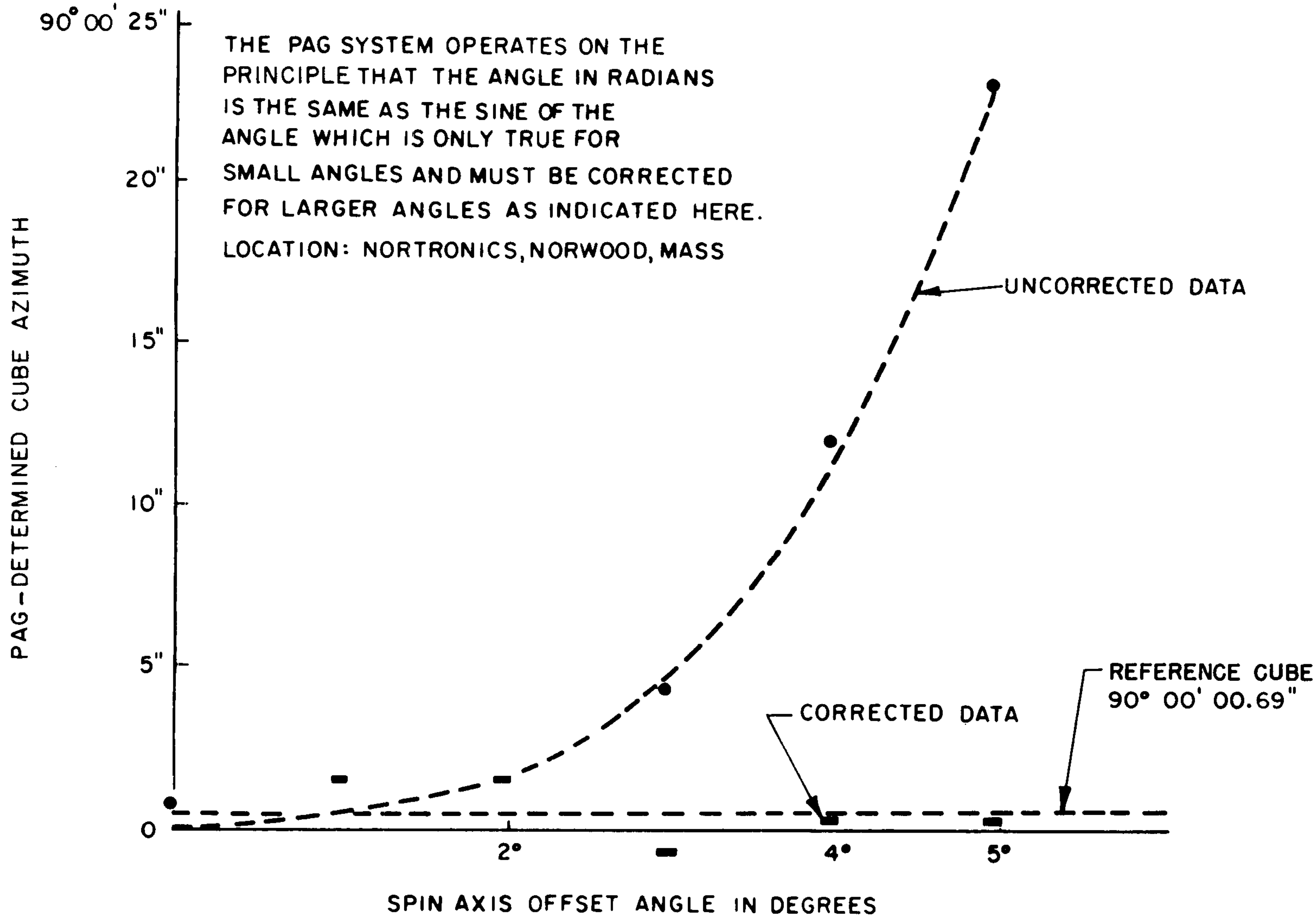


Figure 6.- Azimuth error vs small error for IA offset

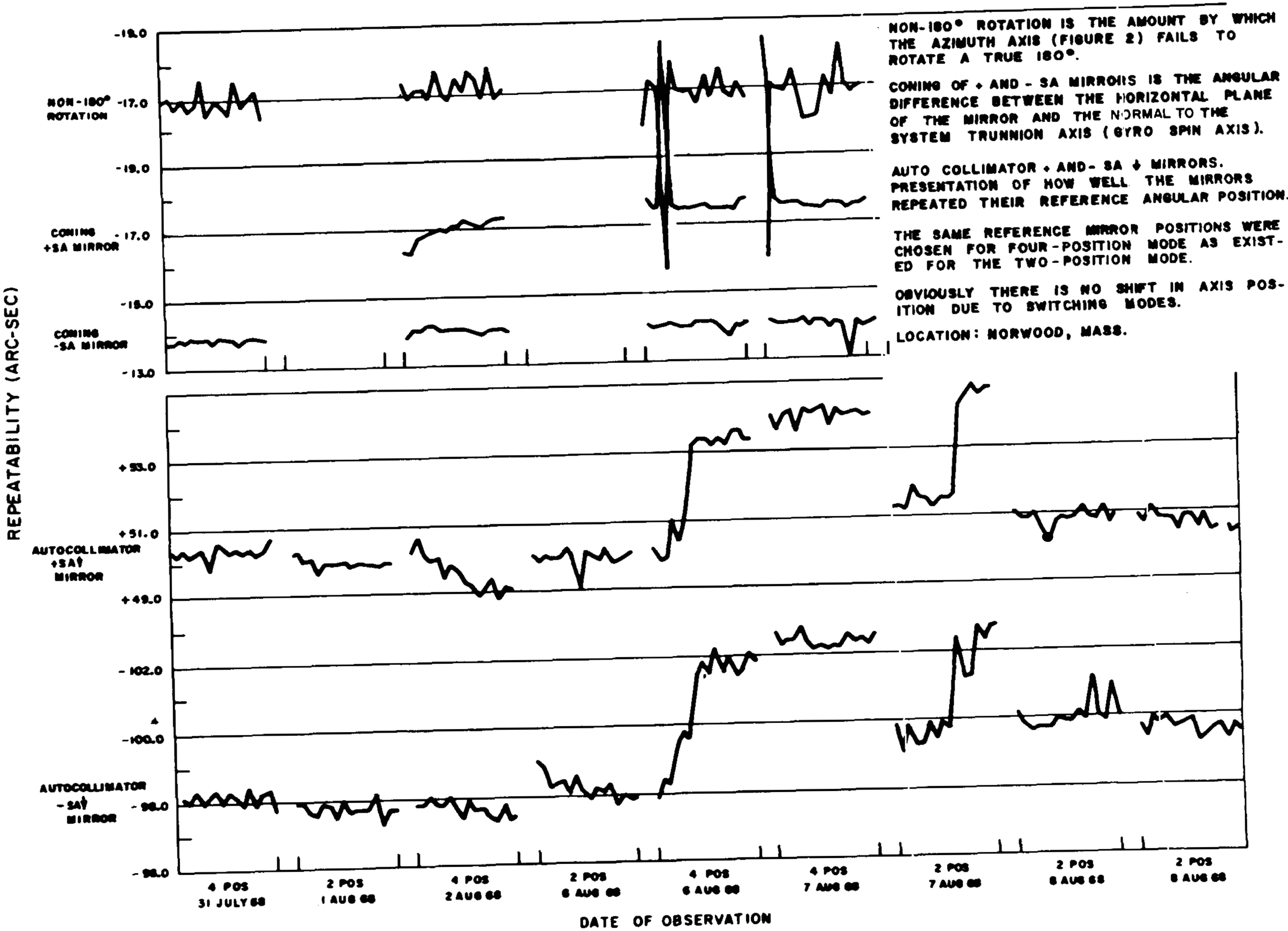


Figure 7. - Mode I and Mode III optical observations

$$\text{Non-180° Rotation} = \left[\frac{\overset{+}{S}A\downarrow - \overset{+}{S}A\uparrow}{2}\right] - \left[\frac{\overset{-}{S}A\downarrow - \overset{-}{S}A\uparrow}{2}\right]$$

Non-180° Rotation = Amount by which gyro spin axis fails to rotate exactly 180° and therefore, an amount by which the final azimuth data must be corrected.

Coning = Amount of non-perpendicularity of mirror surface to spin rotation axis.

Autocollimator Mirror = Simple plot of autocollimator reading for established reference position.

$S^{+}A\downarrow$ = Spin axis North; output axis down.

Location: Nortronics, Norwood, Mass.

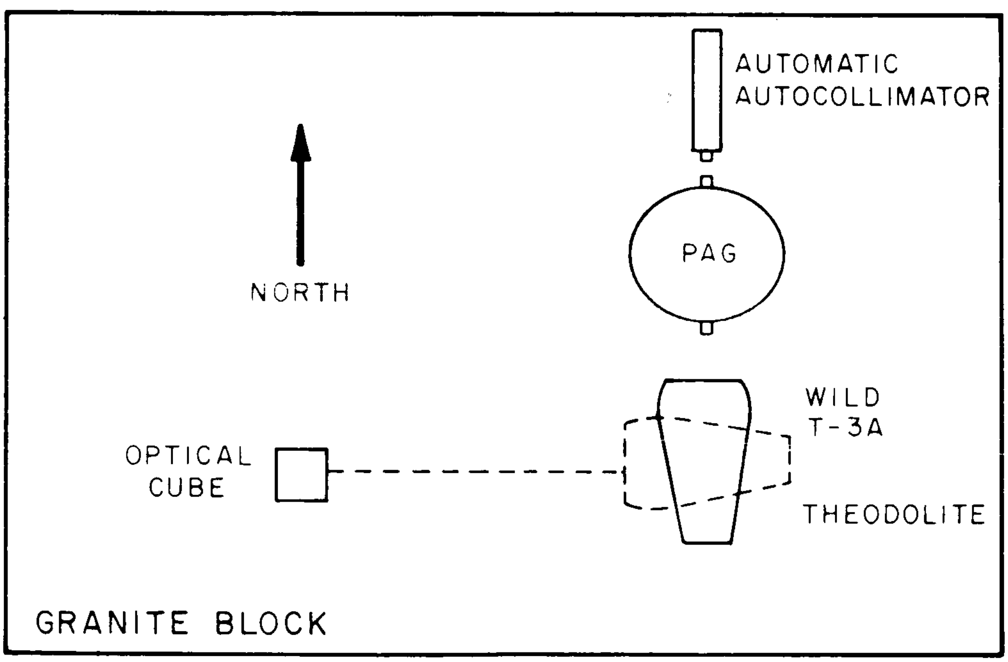


Figure 8. - PAG setup

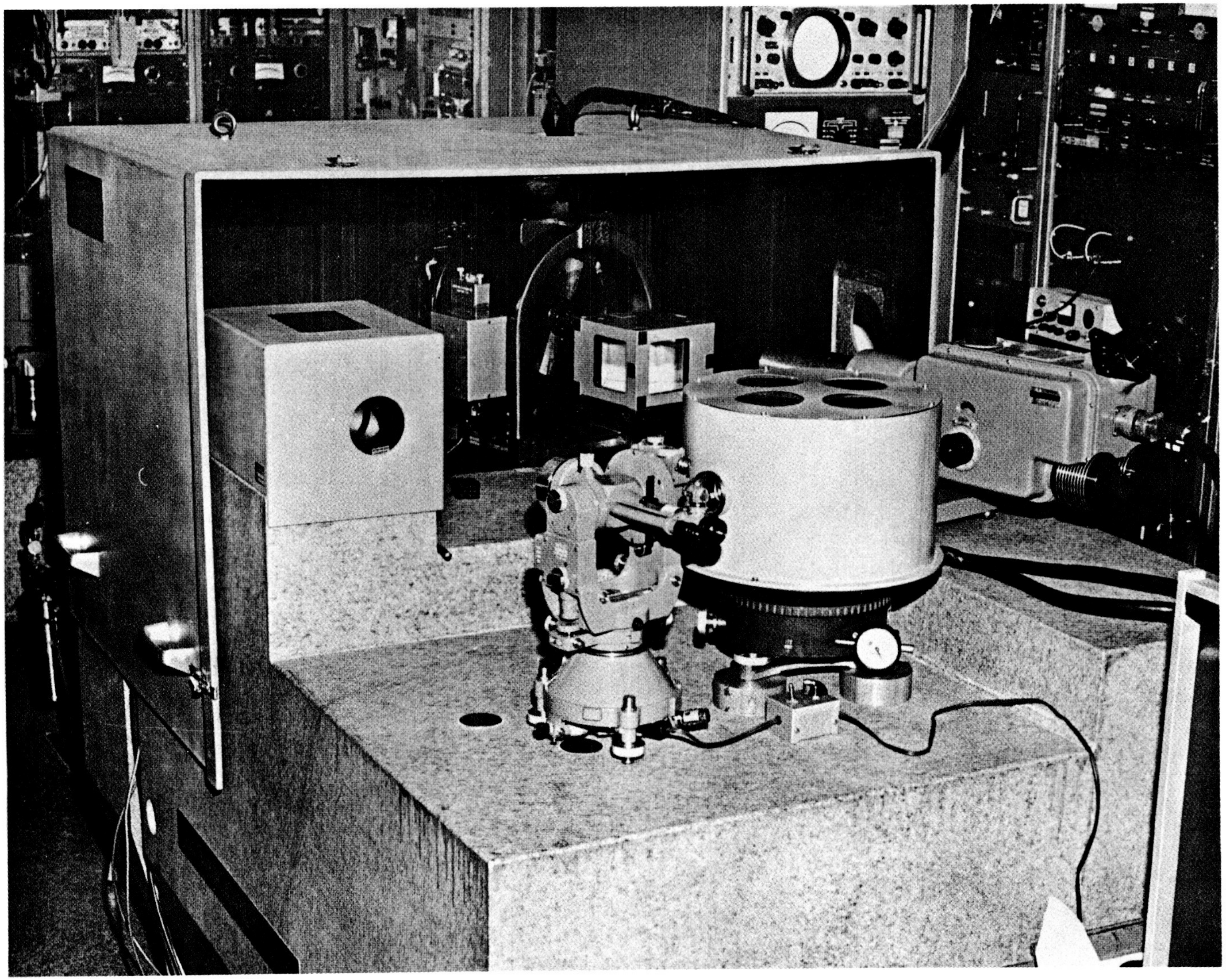


Figure 9.- Photograph of PAG and test area in Norwood, Mass.

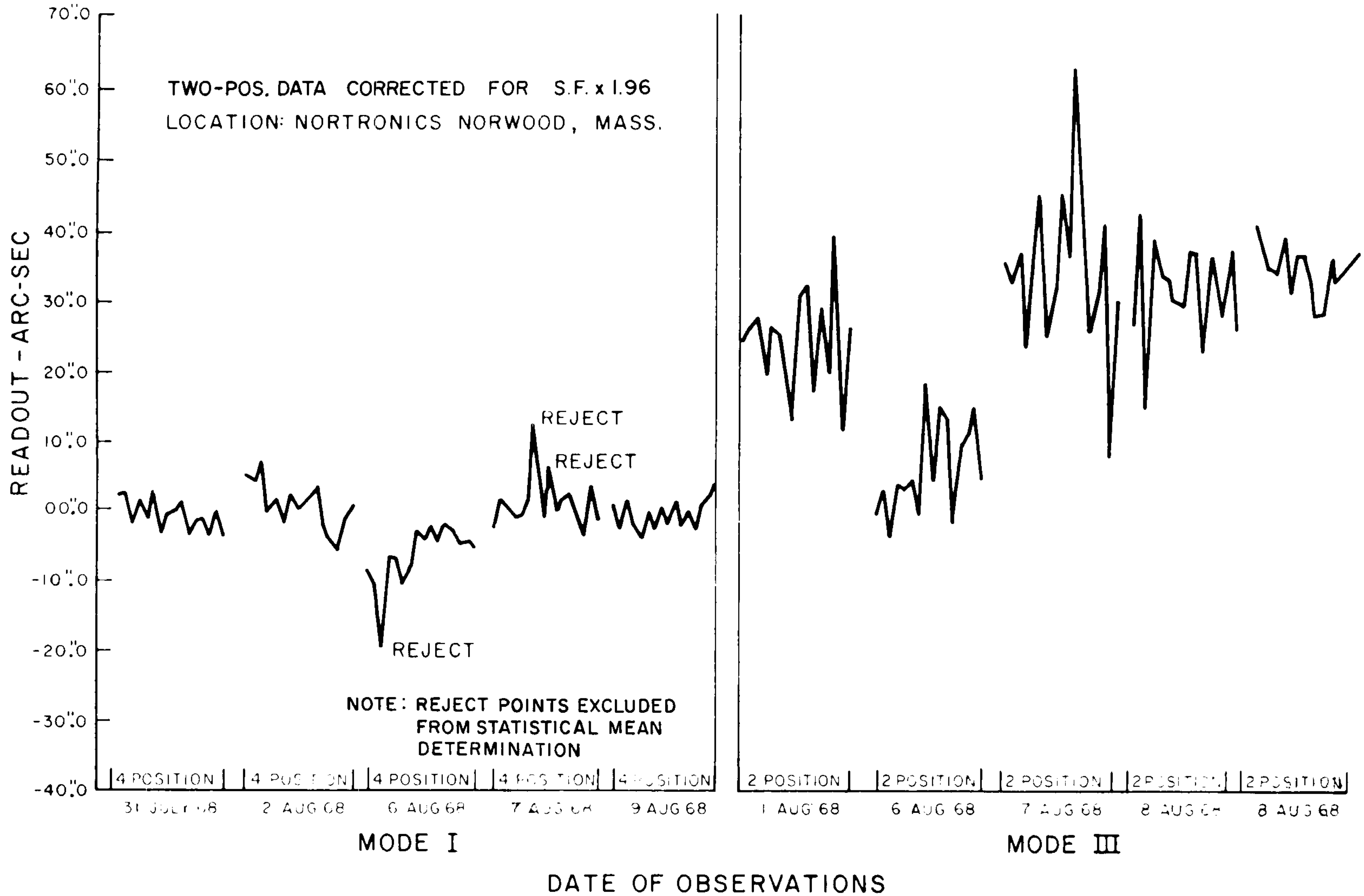


Figure 10.- PAG readout ϕNI

Figure 10 shows plots of point-by-point calibration with transfer to an azimuth optical cube reference. These tests were conducted for 10 days in which the system was shut down (turned off) between calibration. During these tests, the data repeated its mean azimuth calibration in the four-position mode to within 5-arc-seconds bandwidth. It can be seen from the plot of the data that the two-position mode test indicated repeatability of the mean to within 25-arc-second bandwidth. On August 6, a shift occurred in the indexing/positioning of the PAG gyro, the effect noted in the output change was a 10-arc-second spike. On the other hand, a similar shift occurred during a two-position test run, reaching a peak of 30 arc-seconds.

On the 27th of August 1968, the PAG system was set up and operated in the ERC Systems Branch. The unit was leveled and gyrocompassing began. Eighteen transfers were made to a porro prism mounted on a pier in the corner of the room. The azimuth of the porro prism was determined to be 85°28'40.70" with a one sigma of 22.3 arc seconds. The large uncertainty in data repeatability could be attributed to the instability of the column on which the porro prism was located. Theodolite measurement from within the room indicated large azimuth variations due to the porro prism column instability, possibly caused by solar heating of the structure. The use of this reference has since been discontinued. Presently, a porro prism on an interior column of the building is being used. Insufficient data exist to comment on the uncertainty of this reference.

The PAG system testing was continued, Mode I without optical transfers, at NASA/ERC for 24 hours. The bubble level was checked at the beginning and end of the test run. The mean for 104 runs of data was -6.5 arc-seconds with a one sigma of 4.6 arc-seconds.

A comparison of data (16 printouts) taken at ERC and Nortronics is listed in Table II. At both facilities, the data were taken under controlled conditions with no optical transfers, the exception being for the relative difference in seismic activity and floor motions.

Table II

STANDARD DEVIATION vs SEISMIC ACTIVITY

$(\mu g)^2$/cps/sec				Std Dev 1 Set (16) Reading	Max. Hourly Floor Tilt (arc-Sec)
	Vert	Hor N-S	Hor E-W		
Nortronics	1.5	1	1	2.194	0.05
NASA/ERC	5,000	500	10,000	6.04	4.0

As mentioned earlier in the introduction and approach, it was decided early in the test program to collect seismic data with the PAG evaluation. Figures 11 and 12 show samples of the typical seismic data obtained at NASA/ERC Cambridge and PPD Nortronics, Norwood, respectively. The Air Force Cambridge Research Laboratory gathered the data under contract to NASA/ERC. In addition, during the seismic testing at PPD Nortronics, a unique test comparing the seismic activity and the correlative gyrocompass torquer current was gathered. This resulted in the AFCRL report dated 2 June 1969 in which the statement is made, "As can be seen from the graph, approximately one half of the low-frequency content of the gyro is predicted by the seismic trace, squared." The graph referred to is included here as Figure 13. Figures 14A, B, and C and Figure 15 are typical floor motions measured at the two locations (ERC and PPD, respectively) of the PAG data accumulation for Table II. No attempt is made to time-correlate these as the data are not of the same time period. A more detailed report of the test setup, data analysis technique, and data significance tests has been requested of AFCRL. Interested parties can obtain this information upon request.

Several tests were interrupted during August and September because the control logic within the PAG system malfunctioned. The result was that the system would not rest and sample, and the system would only impart a constant slew rate to the azimuth axis or to the gyro output axis. Refer to Appendix A for a report of the repair performed at TRW. The system was returned to ERC during the month of November. A final calibration test run was performed at Nortronics from December 2, 1968, through December 10, 1968. The calibration of scale factor (pot setting) for $\pm 3^{o}$ was performed on December 2, 1968, on a precision ultradex. (See Figure 5.)

On December 5, 1968, two sets of 16-reading four-position gyrocompass data were taken with an optical transfer, see Figure 16. The azimuth of the optical cube was determined to be 89°59'48.98" with a one sigma of 2.614 arc seconds. The second set was determined to be 89°59'48.11" with a one sigma of 2.704 arc seconds. The true azimuth of the cube is 90°00'2.173". The PAG system had a difference of 13 arc seconds from true azimuth. All possible error sources were checked. It was found that the readout had a bias error of 5.88 arc seconds and these data are shown corrected for this error in Figure 17. The system was permitted to continuously print out (see Figure 16). On Tuesday, December 10, 1968, a 16-set transfer calibration from PAG to the azimuth optical cube

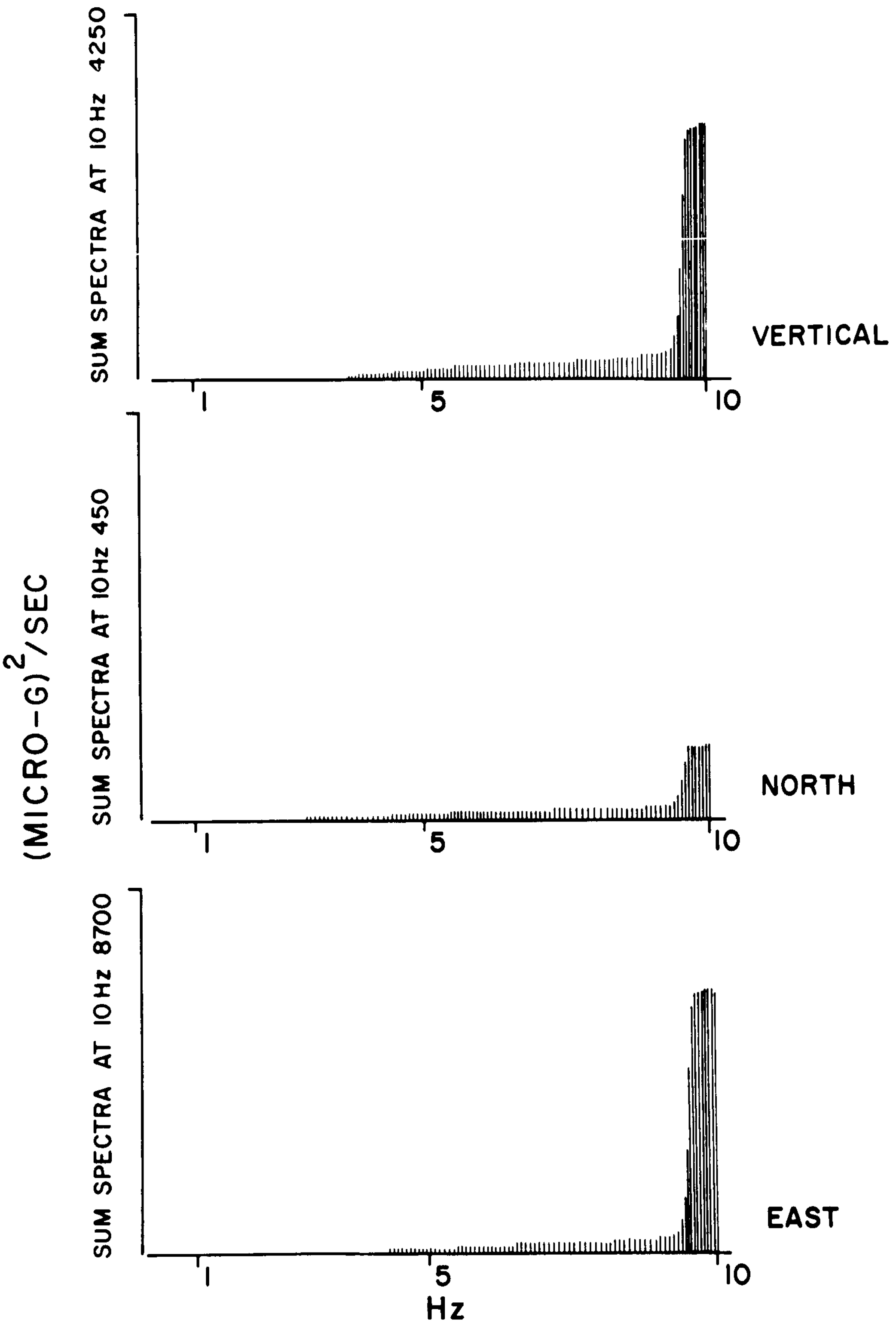


Figure 11. - NASA-ERC seismic data at PAG location

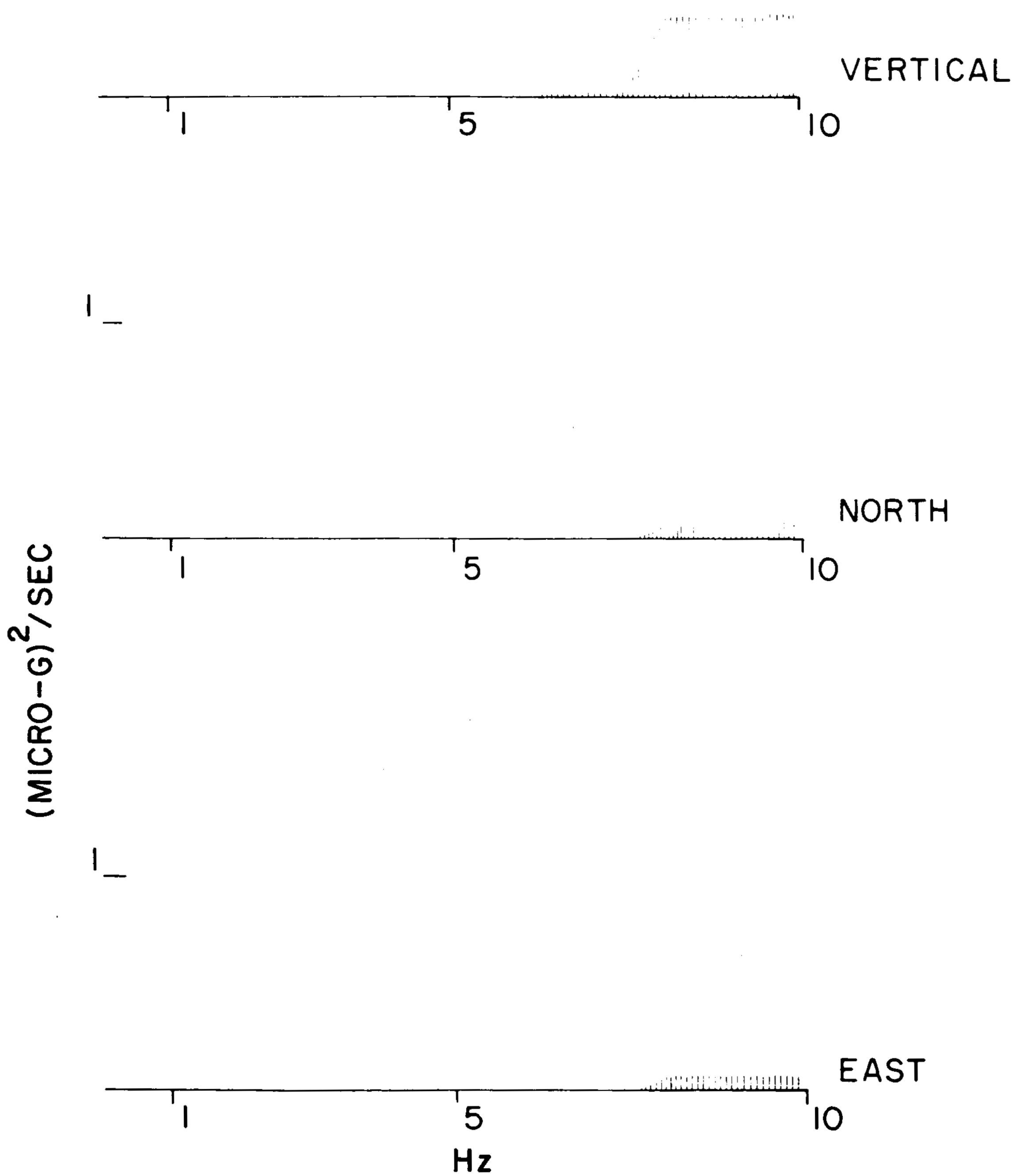


Figure 12. - Nortronics, Norwood, seismic data at PAG location

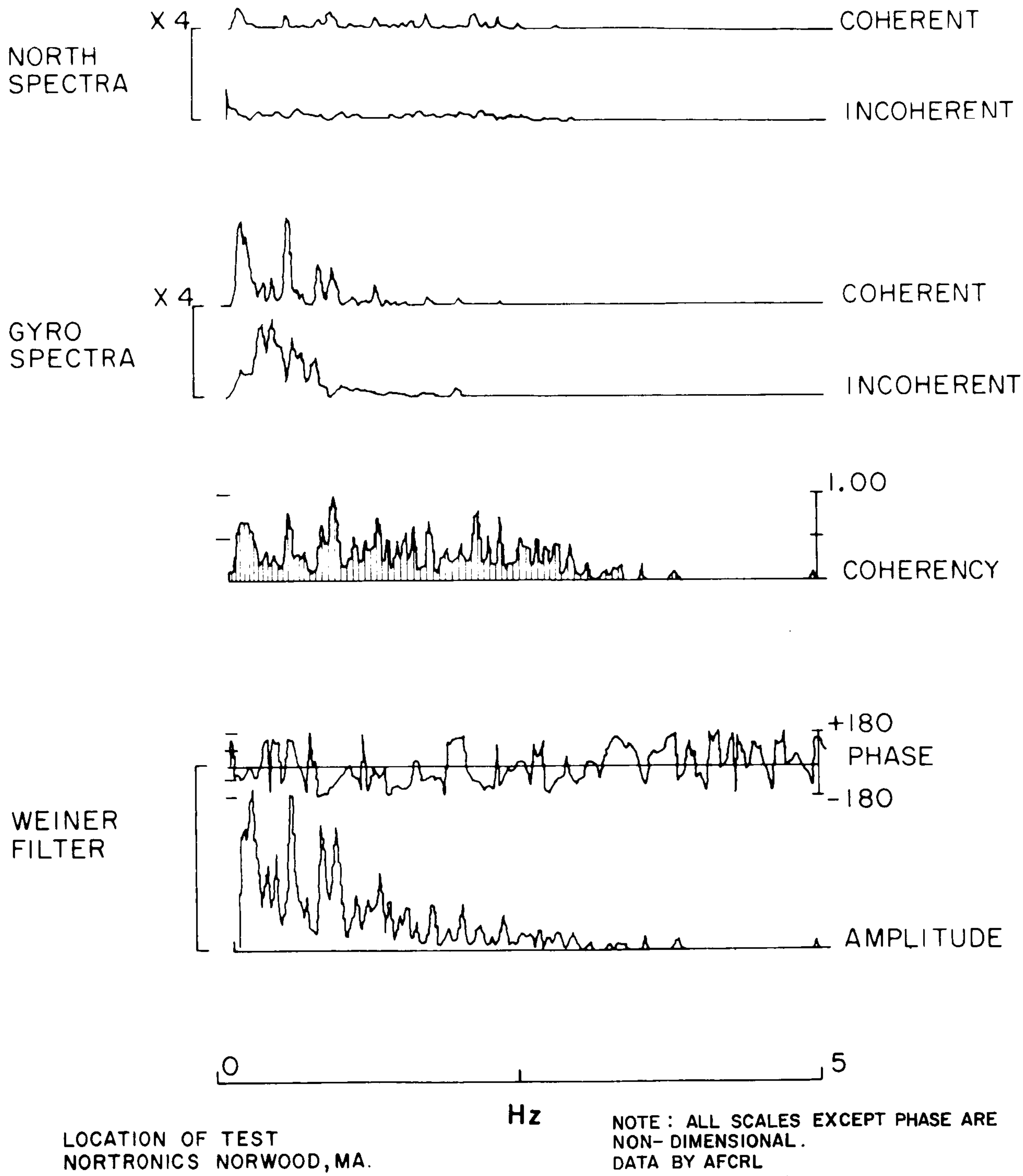


Figure 13. - Nortronics, Norwood, seismic data at PAG location with a repeat gyro monitor (data taken by AFCRL)

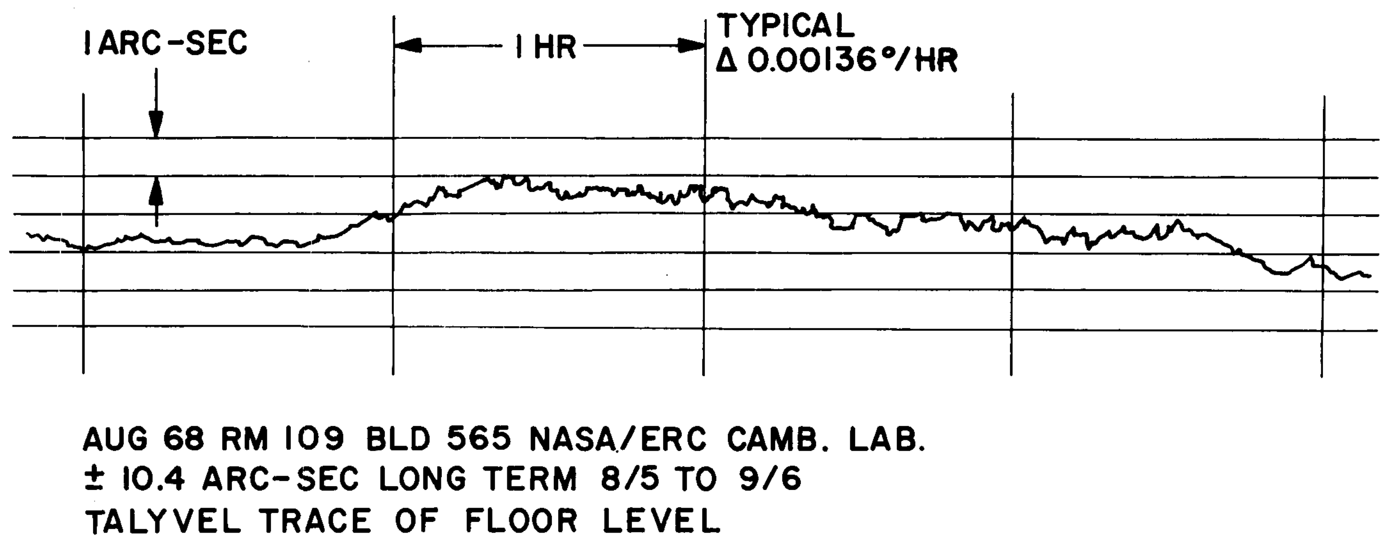


Figure 14A.- NASA-ERC floor tilts at PAG location

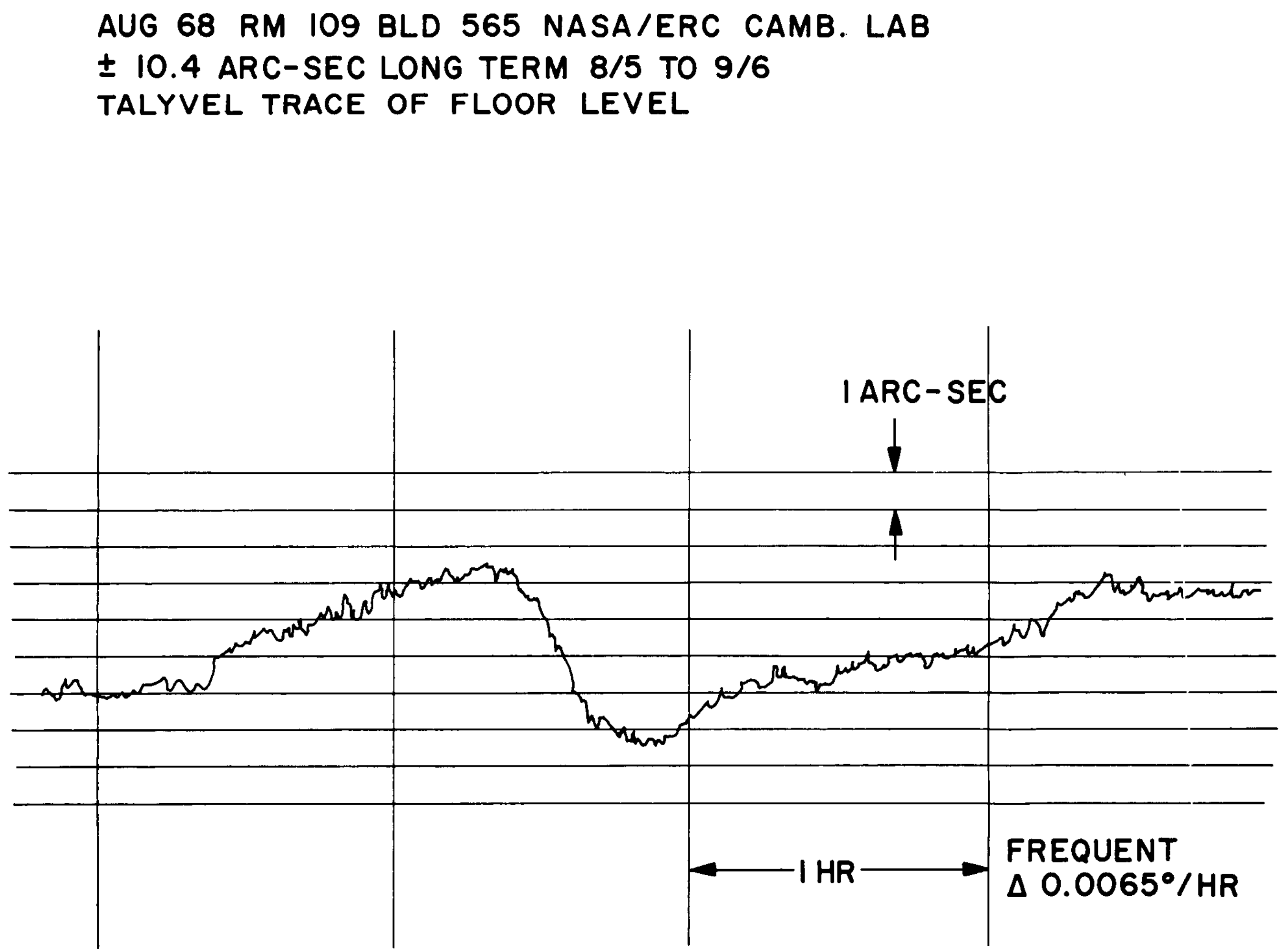


Figure 14B. - NASA-ERC floor tilts at PAG location

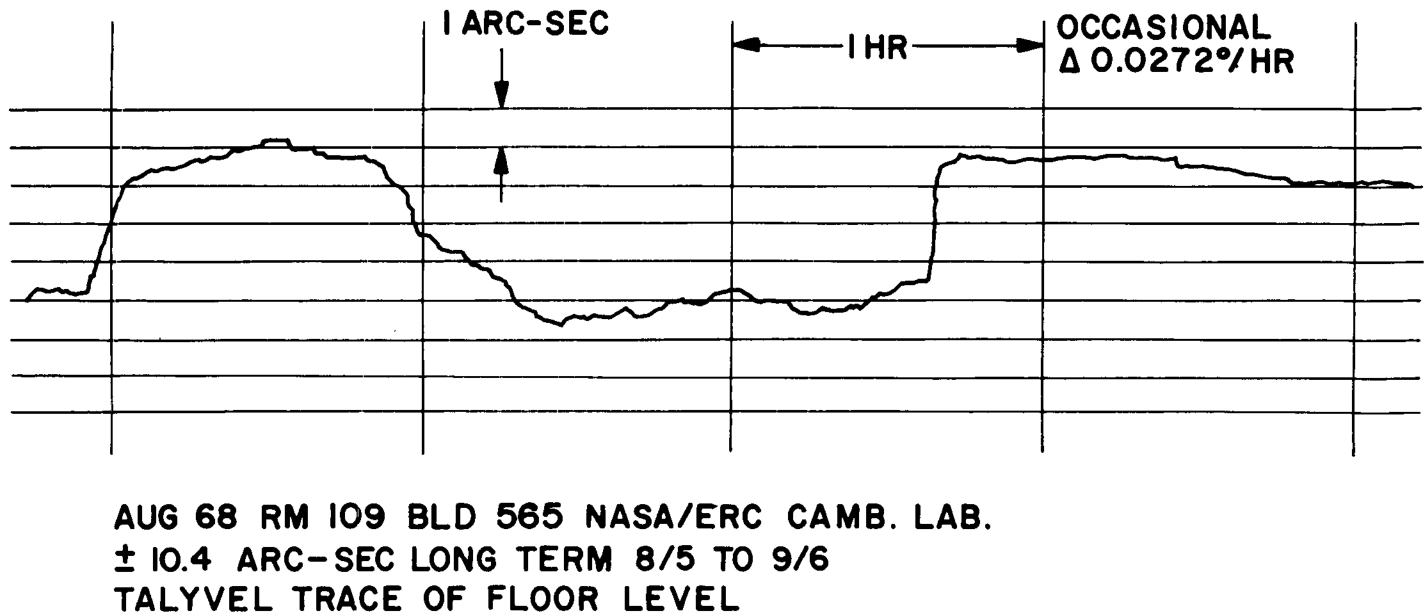


Figure 14C.- NASA-ERC floor tilts at PAG location

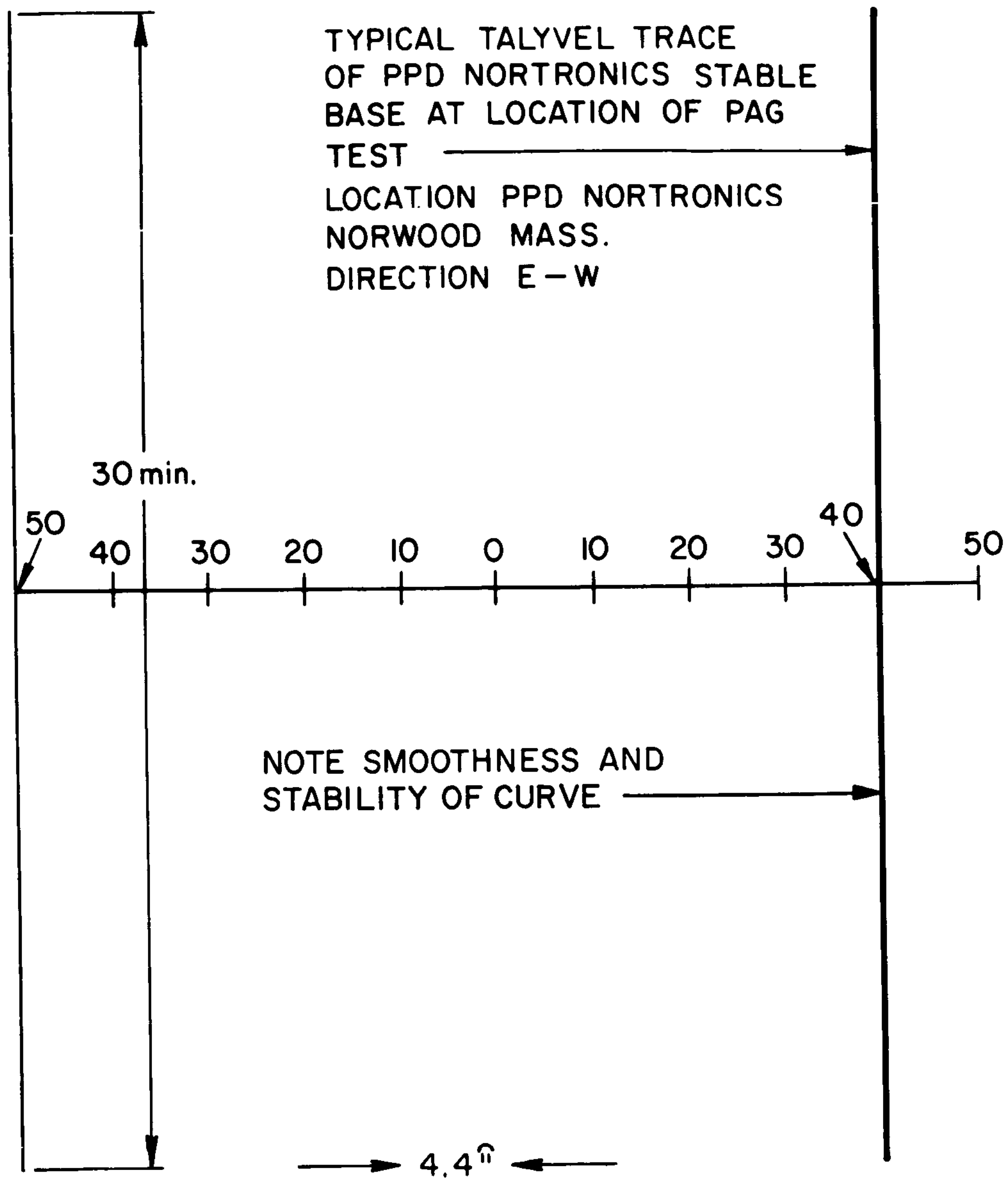


Figure 15.- Nortronics, Norwood, tilts at PAG location

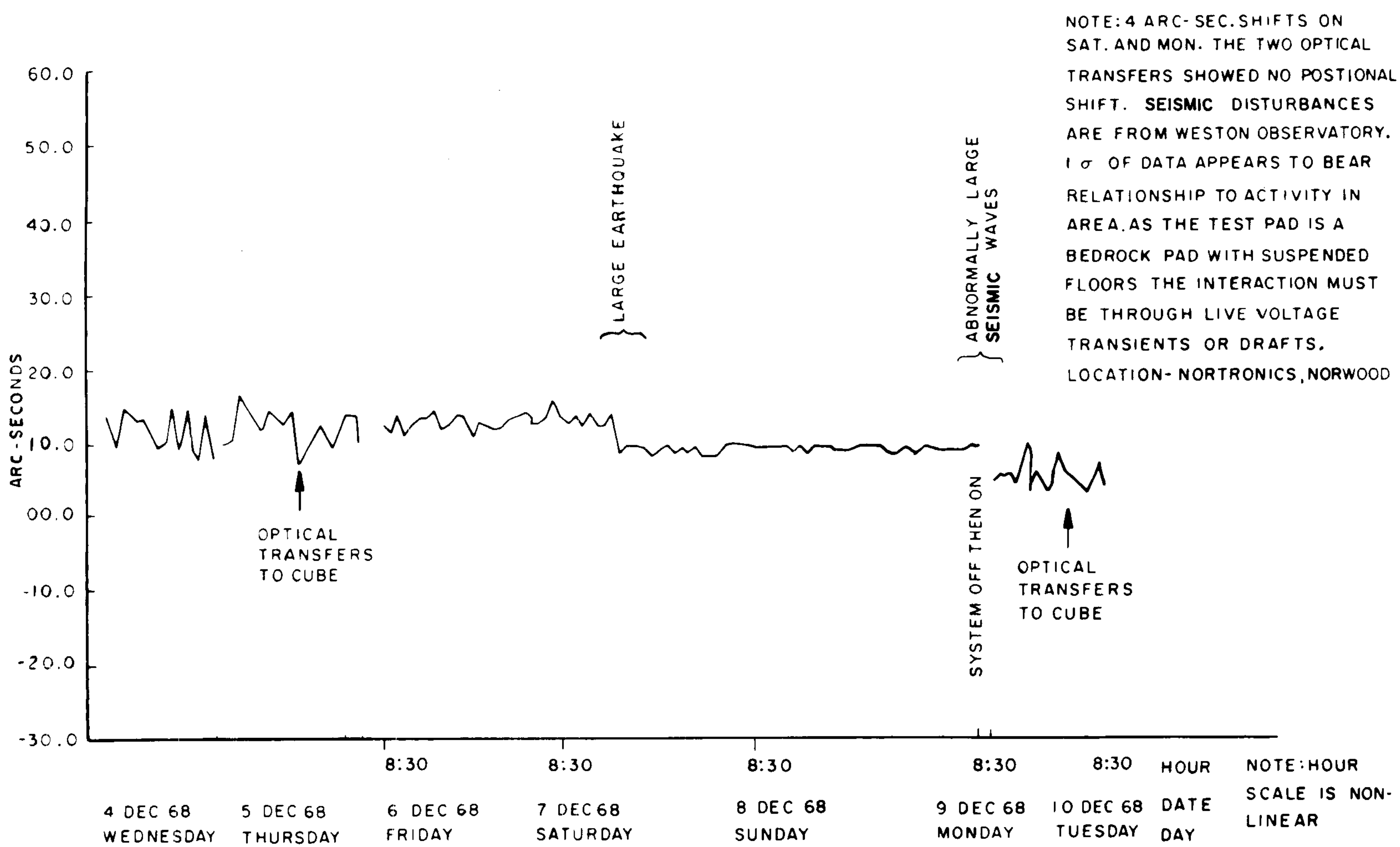


Figure 16. - Mode I December 1968 calibration

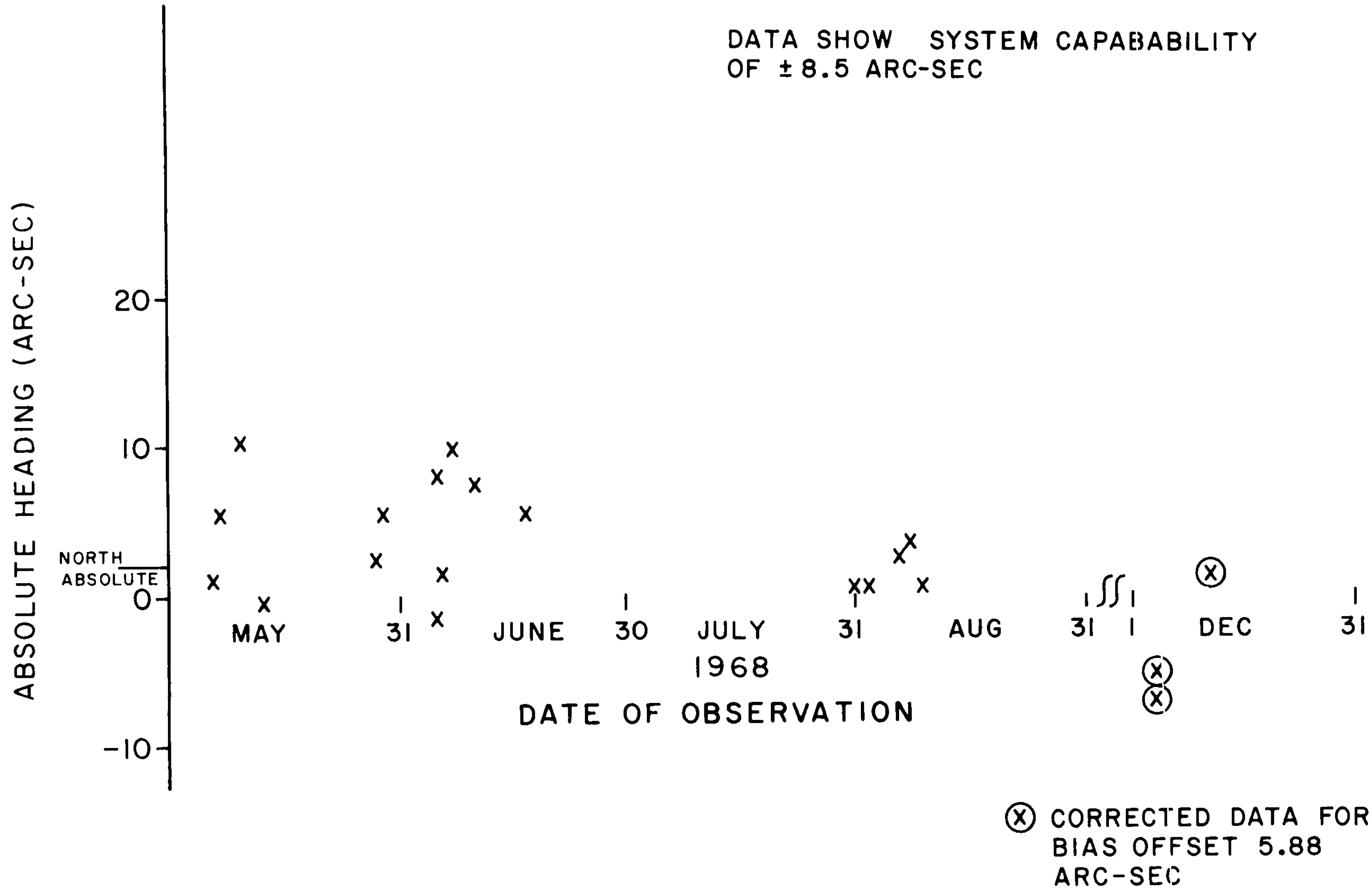


Figure 17. - Mode I absolute azimuth vs time

was performed. The mean azimuth for this set of transfers was 89°59'55.84". An uncertainty between the mean true North and the PAG system still existed. During this test, two problems arose. On Saturday, December 7, 1968, at approximately 3:30 P.M., a 5-arc-second shift in PAG printout was observed. The system was checked for scale factor on December 9, 1968. The mean scale factor for December 9, 1968, was -3589.5 for 1^{o} versus a mean of 3571 on December 2. The scale factors over seven days shifted .68%. It was later learned that a large earthquake also occured at this time.

Figure 17 summarizes all the absolute transfers performed on the PAG system from May through December. The data show a long-term capability of ±8.5 arc second determination of absolute north. Figure 18 expands the data for 31 July through 9 August 1968 to illustrate the misleading apparent short-term capability of 0.5 arc seconds absolute.

Figure 19 is another sample of the short-term repeatability of the PAG system. From these data it can easily be shown that the PAG system has a repeatability of ±0.5 arc seconds. For this test the unit was located under a draft shield and was not moved but was shut down between successive tests. Note that the mean value is 7.03 arc seconds off from true azimuth.

Figure 20 shows a typical sample of point to point PAG system data output with and without draft shielding. It must be noted that the 3-to-1 improvement was obtained in a precision laboratory where every attempt is made to maintain the lab ambient draft free and at a constant temperature. The mean value shift is not significant as the unit was moved between tests. Figure 21 is mode VI data which are stationary (non-rotating) data readout taken as the unit warms up from a shutdown condition. Two curves were obtained, one with the system completely off then turned on (Curve A) and the other with the system off but the gyro wheel running on an external source (Curve B). The data results show in either case the warmup took 1 hour and 45 minutes. From these data we conclude 1 hour and 45 minutes to be the minimum on-time before reliable data can be obtained. In the time lapse of 1 hour and 45 minutes, however, functions such as leveling and azimuth adjustments can be made.

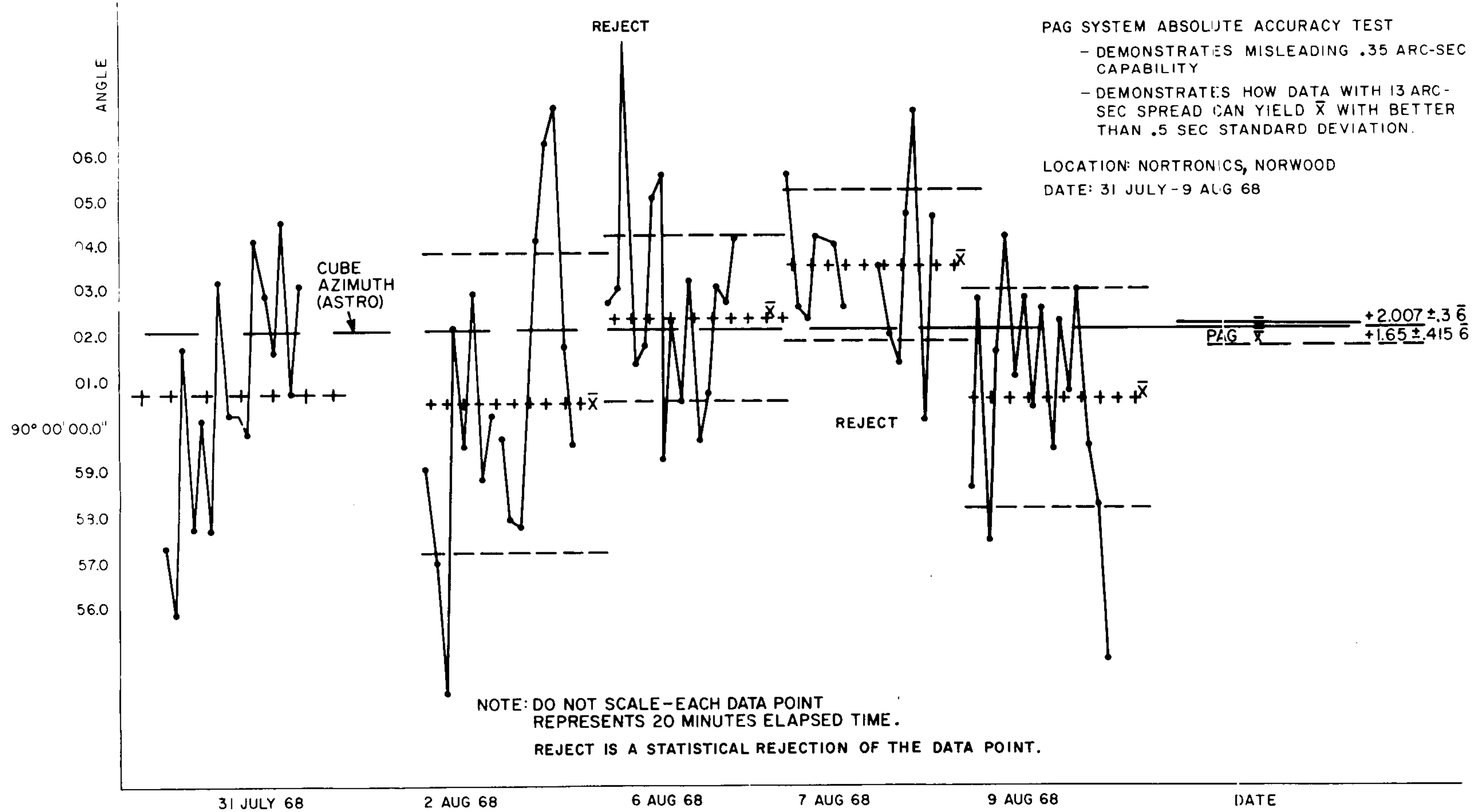


Figure 18.- Mode I, July 31 through August 9, 1968

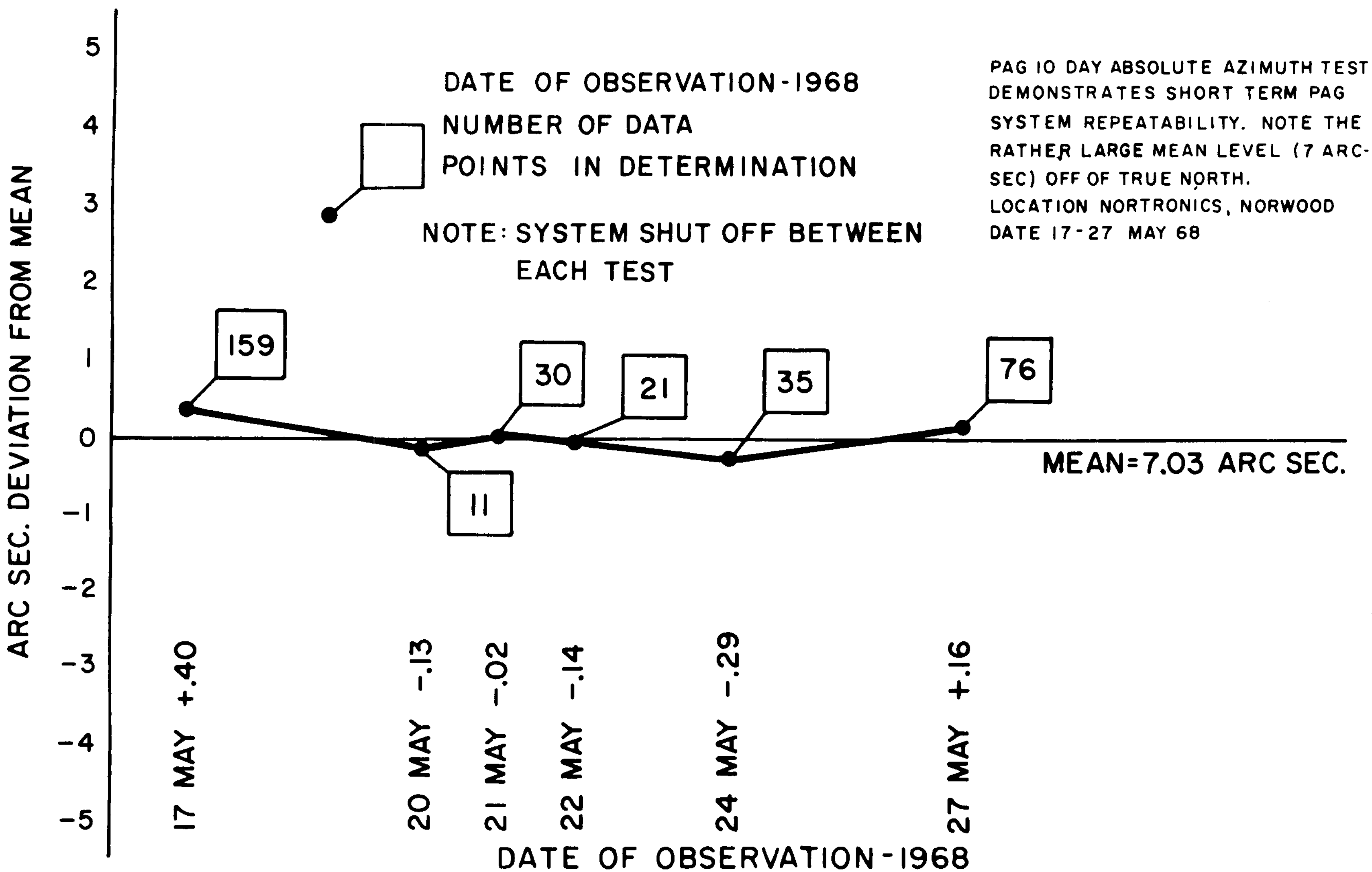


Figure 19. - Mode I Short-Term Repeatability

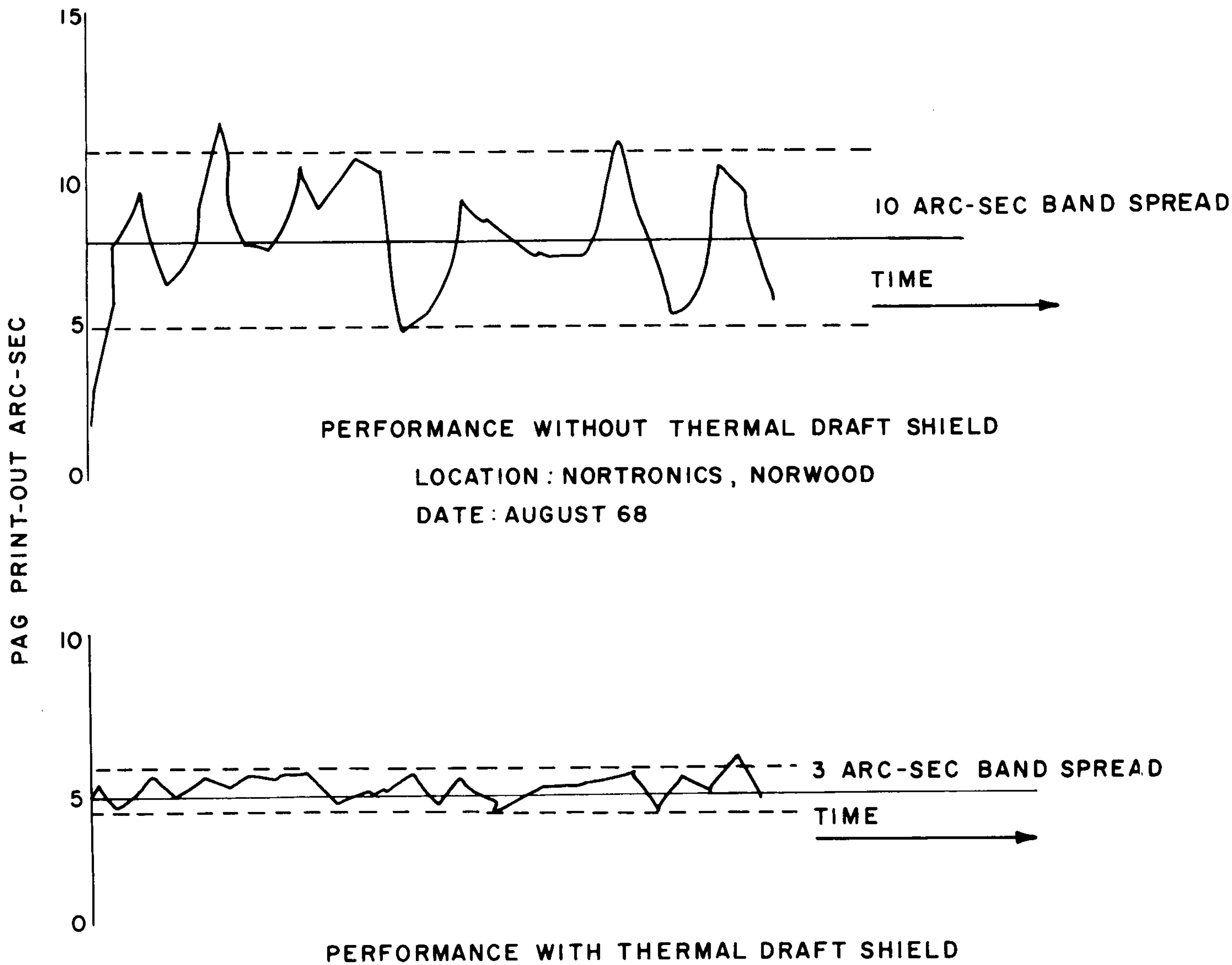


Figure 20. - Mode I PAG thermal draft sensitivity

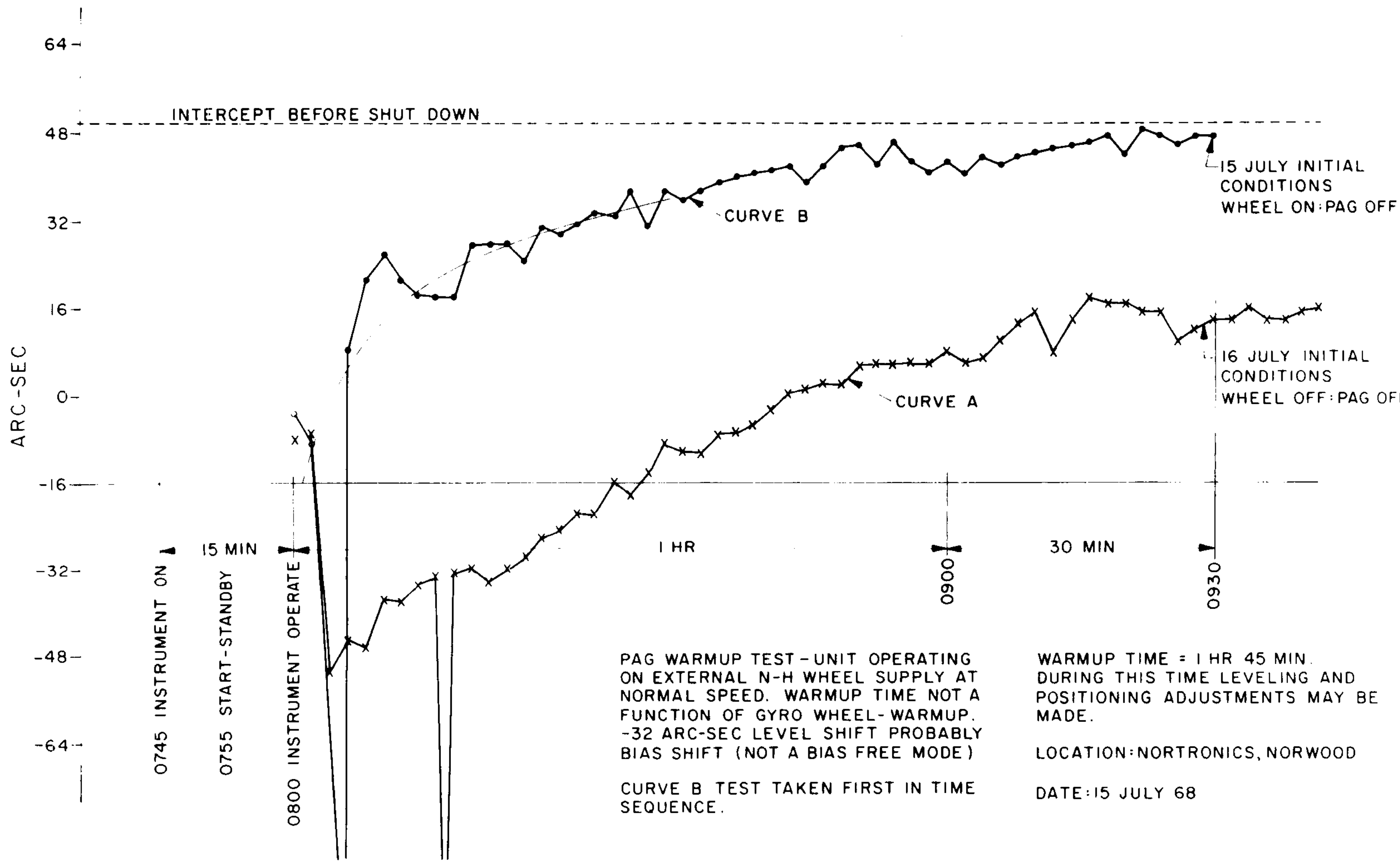


Figure 21. - Mode VI PAG Warmup vs Time

RECOMMENDATIONS

It is recommended that further test and evaluation of the TRW/PAG system be performed. This system as now designed with proper monitoring of optical sequences and supply voltages, could be used to provide a lab azimuth reference accurate to within ±8.5 arc seconds. As a portable lab azimuth reference, it is very good and should continue to be used for this purpose with care. Qualified operators should be selected and the operation of this system should be restricted to these persons. This system could be developed for use as a field all-weather azimuth reference for systems alignment with potential accuracy of 20 arc seconds. However, the PAG must be fully protected from environmental factors. Additional tests, such as line voltage and frequency sensitivity, magnetic field sensitivity, etc., should be performed.

CONCLUSIONS

The following list of information has been gleaned from the data obtained and testing performed with the NASA/ERC PAG system:

(1) A long-term absolute azimuth reference accuracy of ±8.5 arc seconds (8 month period).

(2) Short-term system shifts of up to 5 arc seconds with no apparent cause have been observed.

(3) The system when used as a two-position gyrocompass indicated an azimuth capability of ±15 arc seconds.

(4) The system when used in the dead reckoning mode, mode VI, showed a ±25-arc-second capability.

(5) The programmable platform sensor packages (PSP) has shown a high sensitivity to drafts.

(6) The basic system warmup time in a lab environment (70°F) is 1 hour and 45 minutes.

(7) The adjustable base exhibited creep and was abandoned as an adjustment technique.

(8) The PAG system is susceptible to floor vibration and motion both in data spread and possibly in shifting.

(9) The PAG system must be used basically on a North-South spin axis alignment or errors due to latitude pot calibration inaccuracies and radian to sine difference are significant.

(10) Operating technique is important. Proper leveling, clamping of cables, and tightening of mechanical locks are important. The system should only be used by properly trained personnel.

(11) It is possible for the sensor package positioning system to shift, so a constant monitor of the mirrors should be kept.

(12) Field use of the existing system in most normal exposed environments is inadvisable, unless a large degradation of performance is acceptable (arc minutes).

APPENDIX A

REPORT OF REPAIR ON ERC GYROCOMPASS MADE BY TRW SYSTEMS GROUP

The ERC gyrocompass was returned on October 15, 1968 for repair. The following malfunctions were observed and repaired in the manner indicated.

(1) All visual displays were inoperative except the four 12-volt position indicators. The printer was also inoperative (no print command). The manual slew command for the rotation axis was inoperative. A terminal in the power supply assembly was broken. The unit otherwise operated normally.

(2) A broken wire (+5.3-volt line) at J15-B-26 and J17-B-16 was found and repaired. This restored the visual display and print command to normal.

(3) The card connectors and card connection pins were cleaned with Freon and the manual slew command became operative.

(4) The broken terminal in the power supply was replaced.

(5) The system was operated in VFC test and in gyrocompass modes. The gyrocompass mode produced unsatisfactory results with regard to scale factor and accuracy. A check of the gyro torque loop showed excessive noise at the gyro torque amplifier output. The problem was traced to a bad diode in the -12-volt regulator, which was replaced. (The diode was one of a matched pair; therefore, both were replaced.)

(6) A check of unit scale factor still proved unsatisfactory. The cause of this was the wrong gain setting in the VFC. After returning the gain to 1.0, the scale factor checkout was satisfactory.

(7) Bad +5.3-volt lamps (3) were replaced in the display and +12-volt lamps (2) were replaced in the position indicators. A wire was replaced on the display driver card to reactivate the minus sign.

(8) The unit was operated in VFC and gyrocompass and behaved normally. The reed switches, null detector, and servo loops were checked to determine the cause of the

problems observed at ERC but no additional difficulties were found.

(9) The unit was checked for scale factor on the dividing head and for accuracy against the R-2 facility porro. The results were satisfactory.